

Polarization in GRB Afterglows

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1 Introduction

Over the past five years a clear and consistent picture of the cause of Gamma-Ray Burst (GRB) afterglows has emerged. The afterglow is thought to originate in a decelerating relativistic fireball and is generally believed to be synchrotron emission (see e.g. [1, 2] for a review). Synchrotron emission can, under favorable conditions, be up to 60 – 70% polarized (e.g. [3]). It is therefore natural to expect that the GRB afterglow emission might show some degree of polarization. The amount of polarization may depend on the magnetic field structure and its regularity, the geometry of the collimated outflow and on the properties of the local burst environment. It is important for our understanding of the GRB phenomenon, to be able to account properly for all polarization from these sources. It may, in particular, provide important information on the geometry and magnetic field properties of the bursts.

2 Models

Several models have been suggested in order to quantify the polarization that might potentially be observed from bursts. In addition to the intrinsic afterglow polarization, it is also very important to account for the polarization that might originate in our Galaxy as well as in the host galaxy of a given burst. We will briefly discuss these possibilities in turn.

i) Coherent magnetic patches: The relativistic shock is composed of several causally disconnected patches or domains, each patch having a regular magnetic field structure and exhibiting a polarization level up to $P_{\max} \sim 60 - 70\%$. An observable collection of N patches would result in a net polarization of $P \sim P_{\max}/\sqrt{N}$, with the size of the patches growing at the speed of light [4].

ii) Microlensing: If a burst is microlensed a particular magnetic patch might get briefly magnified resulting in a relatively short episode of variable polarized emission [5]. The degree of polarization at maximum depends on the number of magnified patches.

iii) Interstellar scintillation: is also able to produce polarization in the radio of

the order of 10 – 20%, about a week after the burst [6].

iv) Collimated fireballs: Recent evidence suggests that the relativistic outflow associated with a GRB is collimated. If the observer’s line of sight happens to coincide with the outflow symmetry axis, no net polarization is expected. If the line of sight, on the other hand, makes an angle with the collimation axis, the symmetry is broken, and a net polarization may arise. It can be shown [7, 8] that there will be at least two peaks in the polarization light curve, the first one arising when the observer only receives radiation from that part of the relativistic beam that is inside the outflow geometry. The missing part therefore does not contribute to the total emission and a net polarization arises [7]. The second peak occurs around the break time in the optical light curve and reflects the maximum asymmetry between the emitting areas contribution to the different polarization directions ([7, 8]). A third peak may arise if the jet is spreading laterally [8], but this occurs typically a week after the burst, at which time the flux level may already be too low to allow a reliable polarization measurement. An interesting and testable prediction of the models is that the polarization will decrease to zero in between the first two peaks, accompanied by a 90° change in the polarization angle as the degree of polarization starts increasing again. The collimated outflow model has also been considered in the case of an observer with a line of sight outside the initial opening angle of the jet [9]. A variant of the model, with a bright emission core near the outflow axis surrounded by dimmer wings, results in only one polarization maximum and no change of polarization angle [10]. It is interesting to note that this variant of the model predicts maximum polarization at the light curve break time, whereas the original models with a homogeneous outflow predicts a minimum polarization level at that time.

v) Other: In the case of weakly polarized sources it is important to properly account for the Galactic interstellar polarization. In addition, some degree of polarization may similarly be induced in the host galaxy. In the Galactic case, correcting for this ideally requires observing stars of low intrinsic polarization that are sufficiently distant to ensure an essentially full probe of the interstellar medium, but also sufficiently near the burst location on the sky to allow a meaningful subtraction of the polarization due to the interstellar medium. Alternatively, the interstellar polarization may be estimated from the color excess, $E(B - V)$, that contributes a maximum of $P(\%) = 9E(B - V)$ [11], depending on the line of sight through the Galaxy. Hence, a color excess of at least $E(B - V) \sim 0.3$ is needed to produce interstellar polarization levels of the order of 3%. For most cases to date extinction maps towards bursts imply an interstellar contribution to the polarization up to about 1% at most. Similar correction may be necessary in the host galaxy of the burst, but this is at present much more difficult to estimate. Employing Galactic analogies, one may try to use similar approach as in our own Galaxy and estimate the host polarization contribution from the host extinction, if this can be inferred. Available host extinction estimates (e.g. [12, 13]) indicate that a range of polarization levels of this origin may be expected. The contribution to

GRB	P(%)	PA (deg.)	T	Ref.
980425	0.6	80	~ 8	[14]
980425	0.4	67	~ 25	[14]
980425	0.53	49	~ 42	[15]
990123	< 2.3		0.76	[16]
990510	1.7 ± 0.2	101 ± 3	0.77	[17]
990510	1.6 ± 0.2	98 ± 5	0.86	[18]
990712	2.9 ± 0.4	121.1 ± 3.5	0.44	[19]
990712	1.2 ± 0.4	116.2 ± 10.1	0.70	[19]
990712	2.2 ± 0.7	139.2 ± 10.4	1.45	[19]
010222	1.36 ± 0.64		0.94	[20]
011211	< 2.7		1.5	[21]
020405	1.5 ± 0.4	172 ± 8	1.2	[22]
020405	9.9 ± 1.3	-0.1 ± 3.8	1.3	[23]
020405	1.96 ± 0.33	154 ± 5	2.18	[24]
020405	1.47 ± 0.43	168 ± 9	3.27	[24]
020813	$1.8 - 2.4$	$153 - 162$	0.2-0.3	[25]
020813	0.80 ± 0.16	144 ± 6	0.58	[26]

Table 1: Polarization in optical afterglows. P is the degree of polarization, PA is the polarization angle and T is the time in days after the gamma ray event.

the polarization in the host and the interstellar Galactic medium is however expected not to vary with time. Therefore, observing variable polarization may be taken as an indication of an origin intrinsic to the afterglow.

3 Observations

Measuring the polarization in a GRB afterglow was first attempted in the case of GRB 990123 [16] and resulted in an upper limit of 2.3%. The first positive detection was for GRB 990510 [17, 18], and since then polarized emission has been measured in about 5 other afterglows. The observations are summarized in Table 1. Positive detections have been published in 5 cases and upper limits in 2 cases. Polarization was also measured for SN1998bw/GRB 980425, but these data were obtained at least a week or more from the burst at levels that are a factor of few lower than in other bursts. The polarization level in this case is similar to that observed in other supernovae and is more likely to originate in the non-symmetric expansion of the supernova ejecta.

In addition to the bursts listed in Table 1, there are indications of polarized

emission from GRB 021004, that occurred after the NBSI, but the details of most of these measurements are still unpublished (e.g. [27, 28, 29]).

4 Discussion

Existing afterglow models predict a modest to strong polarization level of $P \approx 10 - 20\%$. In addition, some models based on collimated outflows predict a 90° change in polarization angle between two adjacent maxima in the polarization light curve.

Most measurements to date, however, indicate a low polarization level. In all cases but one is the polarization $< 3\%$ at all times. In addition, the variation in polarization angle within an individual burst is small and never close to the 90° change predicted by the collimated outflow models. In most cases is the angle in fact consistent with being constant. If conditions in the host galaxies are similar to the conditions in our Galaxy, we may expect low polarization levels within the host. It has also been argued that scattering within the host would not be able to produce a few percent polarization within a day of the burst as commonly observed. The path length difference between the scattered (polarized) light and the direct light required to produce a few percent polarization would cause a delay in the polarized light by weeks to months [18].

One measurement of GRB 020405 shows an exceptionally high polarization of almost 10%. This value is obtained a couple of hours following a measurement at the 1.5% level. The strong variation indicates an origin intrinsic to the afterglow rather in the interstellar medium, but it also makes it very difficult to account for using the collimated outflow models [7, 8], in particular as no break was observed in the light curve for the first few days. Alternative explanations may be invoked [23], that do not require a break in the light curve [4, 5].

We conclude that the polarization at the few percent level observed in a number of optical afterglows is most likely intrinsic to the source. Our theoretical understanding of it is, however, still fragmentary and far from complete.

Polarization is becoming routinely measured in optical afterglows and it is of crucial importance to sample the polarization light curve as densely as possible within the first 2-3 days following a burst as this may provide very strong constraints on the afterglow models. It may also provide detailed information on the properties of the local burst environment. Spectropolarimetry is also proving to be an invaluable tool that is already indicating that the polarization may be both wavelength and time dependent [25, 29]. We do, however, need better theoretical modeling to advance our understanding of the polarization properties of the afterglows.

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Discussion

J. Trier Frederiksen: Are there any models involving polarization by interaction with interstellar medium?

G. Björnsson: The basic model is that of scattering of dust grains. The models I have discussed that are related to $E(B - V)$, account for interstellar polarization in our Galaxy and can in principle be applied to the host galaxy contribution too. In most cases, however, is the host extinction rather small, too small in fact to fully explain the observed polarization level. Polarization variability is also an indication of a different origin.

S. Kulkarni: I believe that polarization of the order of 1 – 3% towards stars is not uncommon. Likewise one may expect some degree of polarization induced by the interstellar medium within the host galaxy. Thus the modeling should include a (unknown) foreground polarization (i.e. due to reddening of the afterglow). This may severely limit the conclusions drawn for the few (1-3) data points. Indeed, as you noted the polarization for several afterglows was found to be constant and a few per cent (except 020405).

G. Björnsson: Yes, I agree. The only way I see to distinguish between these polarization sources is to sample the polarization light curve sufficiently densely in addition to spectropolarimetry. This would allow us to monitor variability in the polarization levels as well as changes in the polarization angle that has until now appeared basically constant. It would in particular allow us to follow rapid changes in polarization as was observed in 020405. This however, requires a dedicated effort and given the faintness and rapid fading of the afterglows, will most likely require a combination of a bright burst and favorable observational circumstances.